ÆTHER WIRE & LOCATION, INC.

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BEFORE THE

FEDERAL COMMUNICATIONS COMMISSION

Washington, D.C. 20554

In the Matter of	)	
	)	ET Docket 98-153
Revision of Part 15 of the Commission's Rules	)	
Regarding Ultra-Wideband Transmission Systems	)	

Ex Parte Notification

On 14 March 2001, Robert Fleming and Cherie Kushner of Æther Wire & Location, Inc. (we) met with Bill Lane, Ghassan Khalek, and Gerardo Mejia of the Wireless Telecommunications Bureau (WTB).

We discussed the major points that were made in our reply comments to the NPRM of the above-referenced proceeding. In particular, we advocated that operation of unlicensed Ultra-Wideband devices be permitted under the general emission limits contained in 47 C.F.R. Section 15.209, with the proviso that UWB devices be included in the exemption for intentional radiators of paragraph (d) of section 15.205.

To illustrate significant points, we used slides prepared for a recent Large-Scale Network Workshop and a recent DARPA Principal Investigators meeting. These slides are included as part of this notice.

We presented how 3D Relative Position (*i.e.* Localization) and low data rate sensor communication are the most compelling applications for UWB, because they utilize UWB's unique advantage of having gigahertz bandwidth at low frequencies. It is well understood that gigahertz bandwidth gives centimeter range resolution for position location and the ability to discriminate multipath signals. We stressed that operation at low frequencies below 2 GHz gives the ability to penetrate walls, and to use slower, cheaper (*i.e.* CMOS) integrated circuits. These attributes are critical for future applications, including pervasive Internet connectivity, because the cost, size, and power of wireless links must be fractionally proportionate to the items they connect. We reiterated that society will not enjoy the substantial benefits of these devices unless they are permitted to operate <u>below 2 GHz</u>.

Other parties have commented that small, portable UWB devices will not need to operate below 2 GHz. We stated that this is a <u>false presumption</u>, which is probably due to the inability of others to radiate low frequency UWB signals from a small antenna, and to control their waveforms to avoid GPS frequencies. We showed time and frequency domain plots and an FDTD simulation of the baseband impulse that is radiated from a 4 cm Large Current Radiator when driven by a Gaussian edge. In other words, a physically small antenna can effectively radiate low frequency (~200 MHz) signals.

We also showed time and frequency domain plots of an impulse doublet, which is our chip waveform using CDMA terminology. These plots illustrate how we can place deep 60 dB nulls at the L1 and L2 GPS frequencies. We pointed out how the separation between impulses contributes to low frequencies in the spectrum of a doublet. Moreover, the separation allows the timing tolerances of the circuits to be relaxed, and thereby greatly reduce the cost of a transceiver.

Our slides showed how Autonomous Cargo Manifesting of intermodal cargo containers is a "killer" application that uses the accurate position location capability of UWB. The slides also show measurements of the electromagnetic environment within cargo containers, and how UWB is the only suitable RF technology. We also gave a copy of our CDROM "Archive of Ultra-Wideband Technology" to Bill Lane, as well as a CDROM containing the presented slides.

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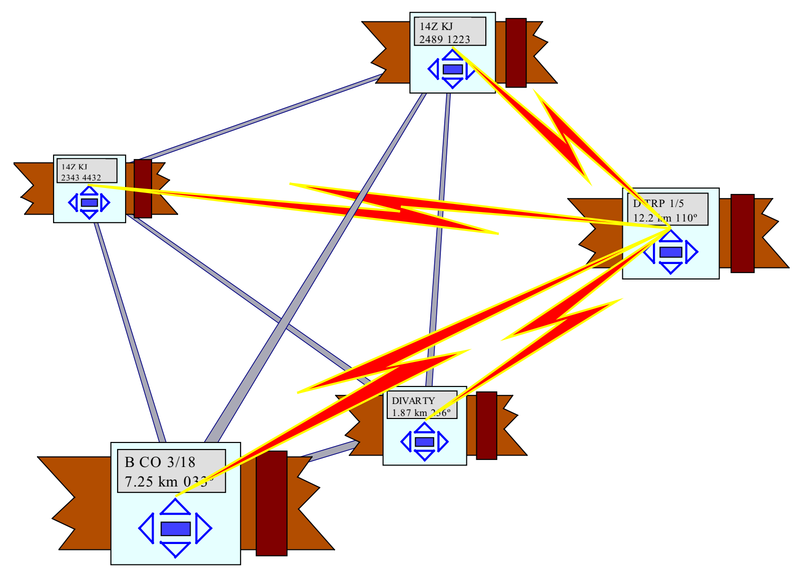
Integrated CMOS Ultra-Wideband Localizers

Aether Wire & Location, Inc.

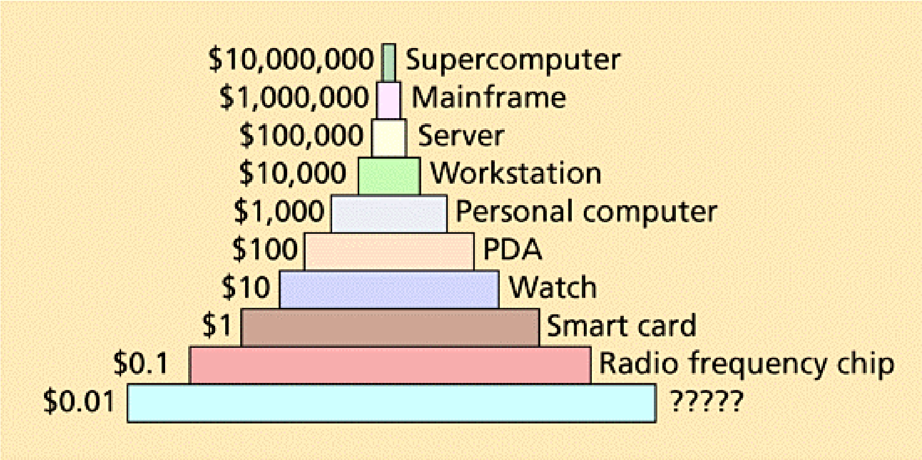
Robert Fleming

Cherie Kushner



Finest-Grained Networking

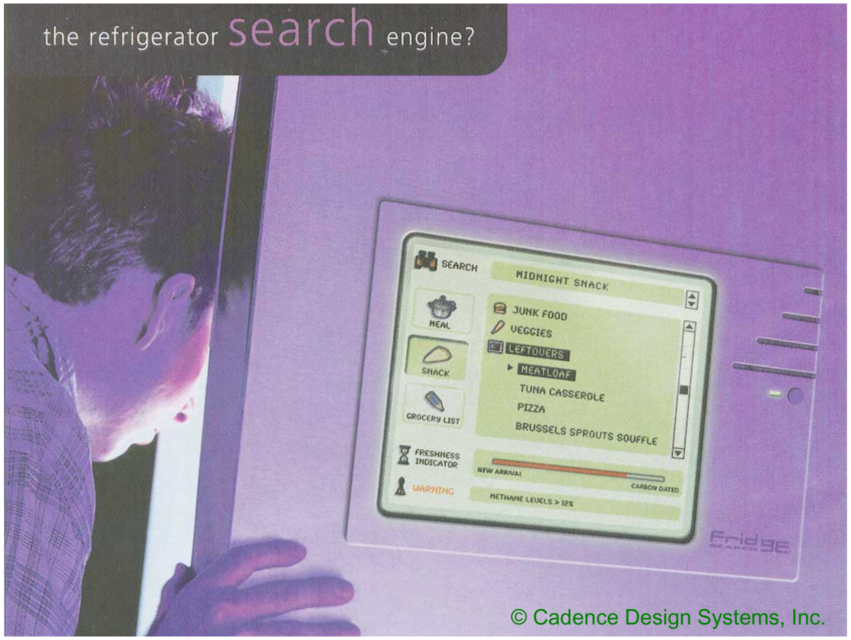
- The next explosion in growth of the Internet will come from connecting to billions of cheap, low-power sensors, effectors, and “smart things”
- Cybernetic servants in the guise of everyday things will interpret and respond to our location, gestures, and movement
- Giga-nodes with short range / low data rates will be the “finest-grained” termination of Gigabit networks
  - » Connectivity will be Wireless
  - » Location is the first measurement a wireless sensor needs
  - » Transceivers must be comparably small, cheap, and low-power
  - » Able to operate in high multipath environments / inside buildings



- Integrated CMOS Ultra-Wideband transceivers (Localizers) with precise 3D position location capability are the enabling technology for the “finest-grained” networking of ubiquitous sensors and effectors

Position Location

- Permits intelligent machines to react to their environment
- Extends human senses beyond the limits of sight and hearing
- Enables automating tasks that now require a human for positioning
- Enables location-based Web services



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- Resolution and range proportionate to size and mobility of object
- Most applications want relative location, not latitude and longitude

Hollywood Localizers

Mission Impossible

Advantages of Ultra-Wideband

- UWB Localizers are inherently cheaper, smaller, and lower-power
  - » Transceiver can be Integrated in single low-cost CMOS chip
- GHz bandwidth allows position location to Centimeter resolution
- Precise network-wide timing allows very low duty cycle operation
- Antennas are small because they are non-resonant (~ 2 cm)
  - » Current Mode Antenna can be driven directly by CMOS
- Operation within buildings, urban areas, forests, etc.
  - » Bandwidth at Baseband gives penetrating ability
  - » No deep fading nulls – reduces path loss from $1/r^4 \Rightarrow 1/r^2$
- Multipath signals can be time-resolved
  - » Direct sequence coding, short chip time, and accurate timing
- Ultra-Wideband maximizes Spectrum Reuse
  - » Non-interfering – energy is spread over GHz bandwidth
  - » Unlicensed spread spectrum bands are filling up

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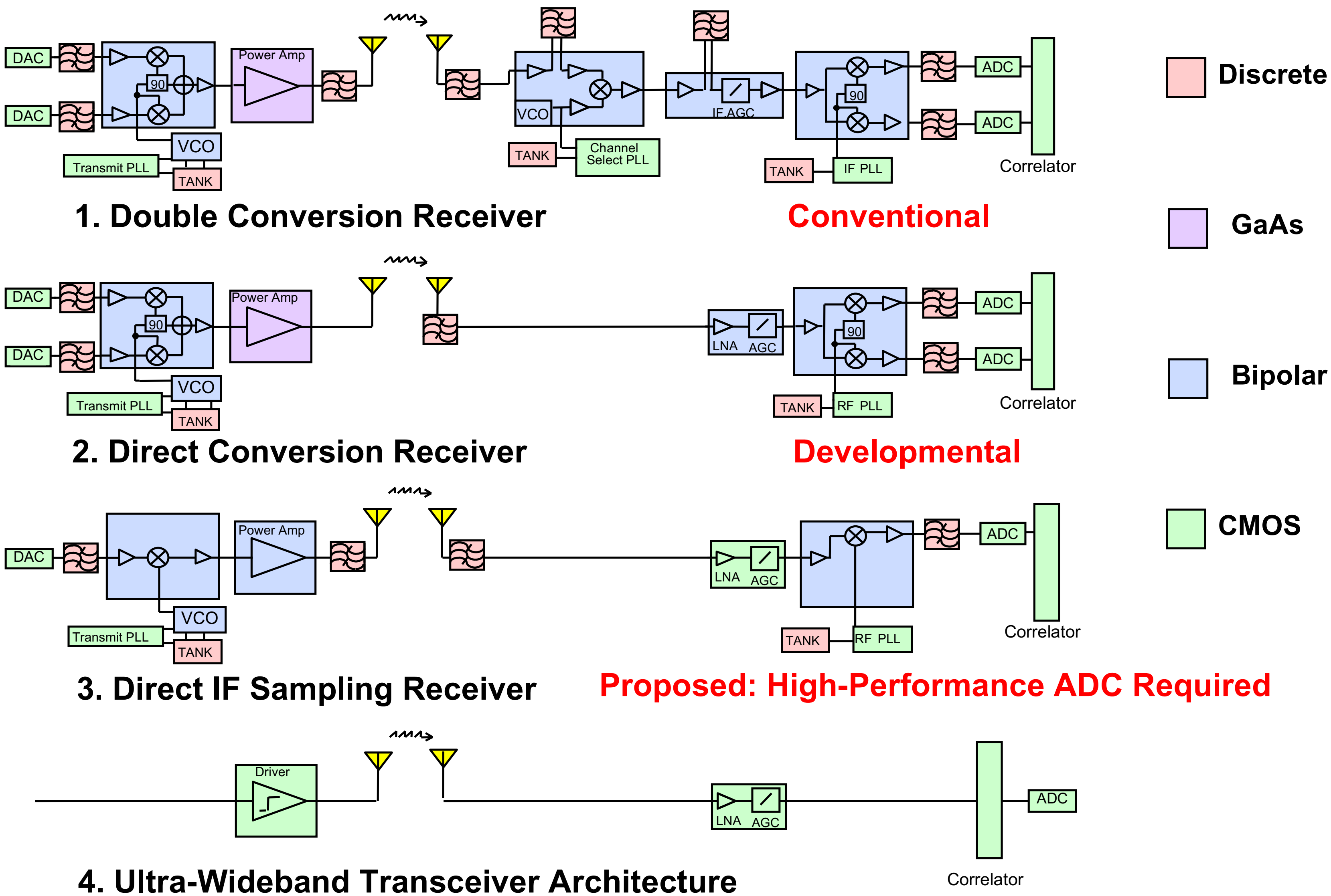
UWB versus Narrowband



Adapted from "The Future of RFIC Transceiver Technology," C. Kermarrec et al,1997 IEEE RFIC Symposium.

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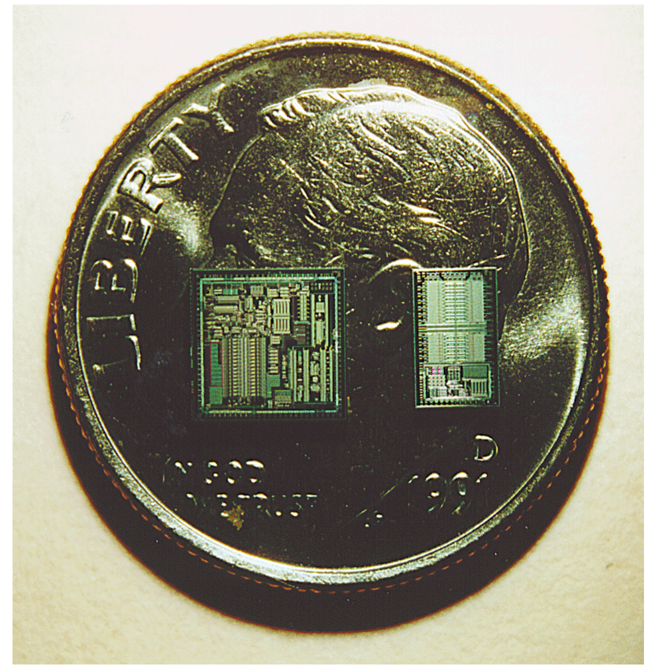
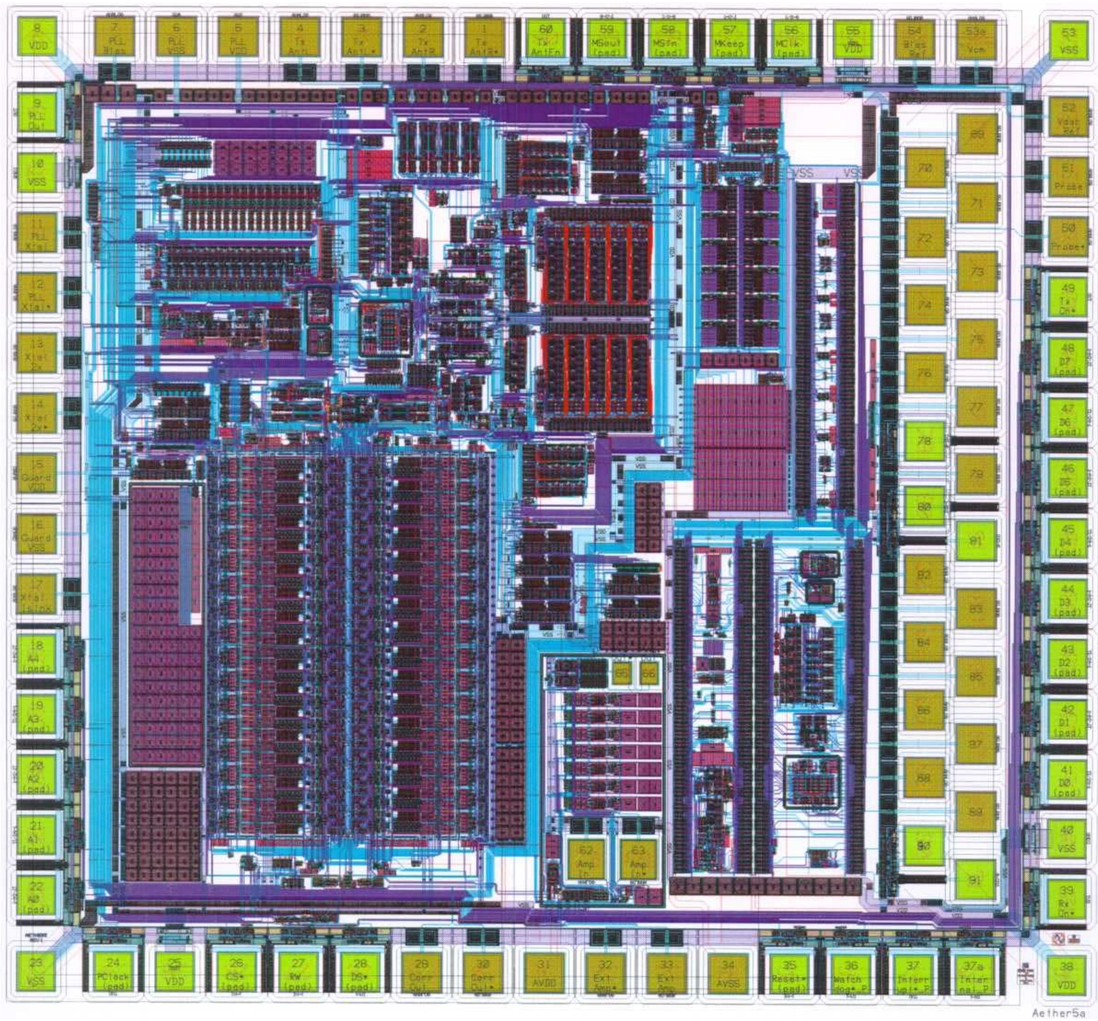
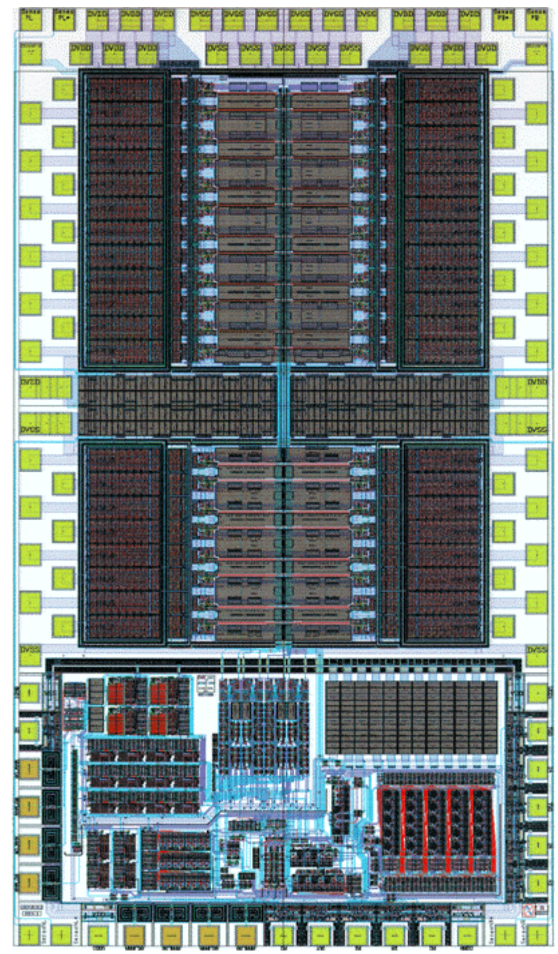
Advantages of CMOS



- Small size & weight
  - » Estimated single chip transceiver die size using 0.18 μ process is 8 mm^2
    - – Includes processor (1 mm^2), 512KB RAM (3 mm^2), and 128KB ROM (1 mm^2)
- Low cost
  - » Current estimated die cost is 50 cents
- Low power – stand-alone battery use
  - » Extremely low static power
  - » No off-chip high current filters or SAWs
  - » Estimated networked idling power is 30 μw
- Rides the digital CMOS cost curve (Moore's law: ½ every 1½ yrs)
  - » Large complexity from high levels of integration
  - » "Software radio" – high functionality from processor/software control

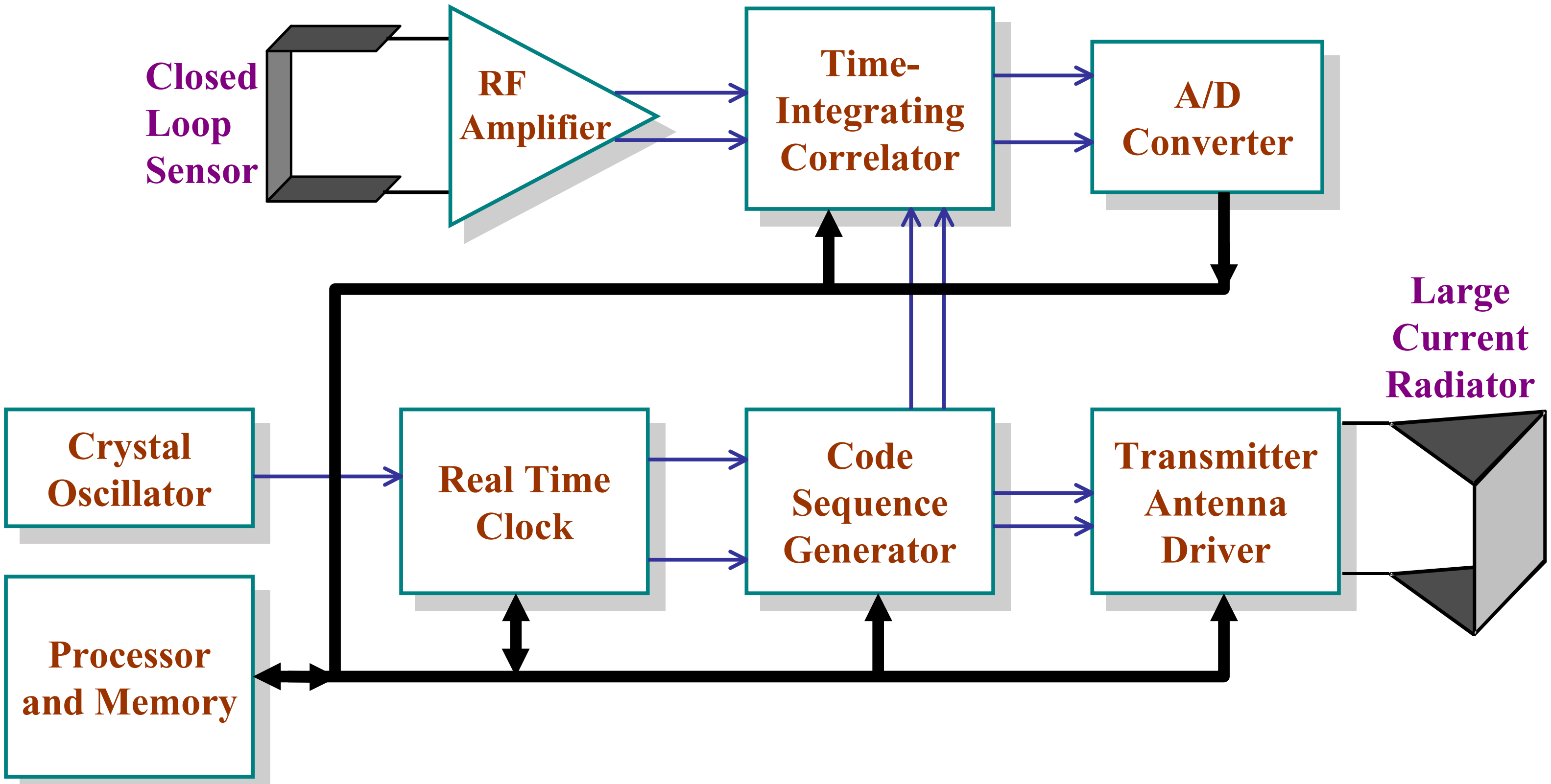
Current Two-Chip Solution


Receiver chip (Aether5)


Transmitter chip (Driver2)

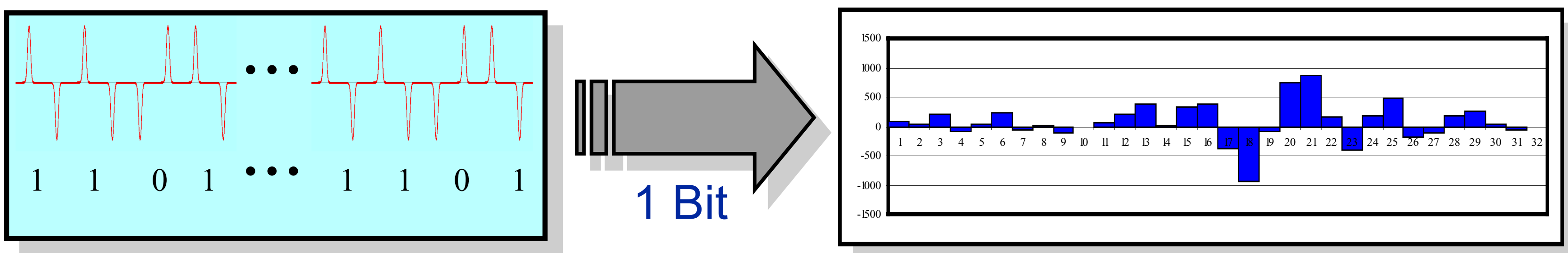
Localizer Block Diagram

- 3D Positions calculated from pair-wise Ranges with information distributed to all nodes within network of Localizers



Technical Approach

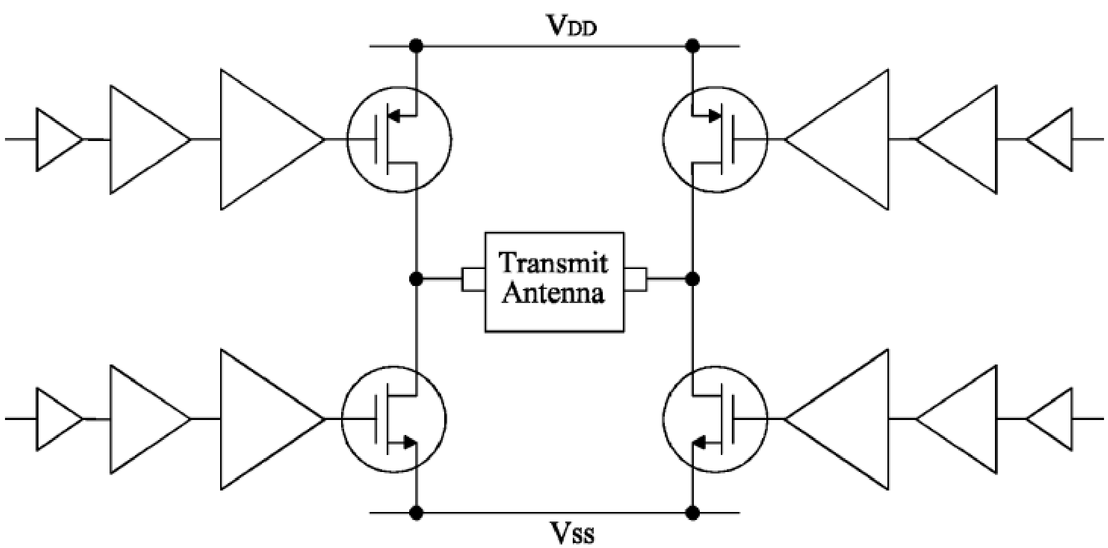
- Episodic transmission of coded sequences of Impulse Doublets
  - » Typical 1K sequence of 10 ns chips lasts 10 µs
- Coherent reception using Correlation
  - » Typical 30 dB Process Gain with 1K sequence

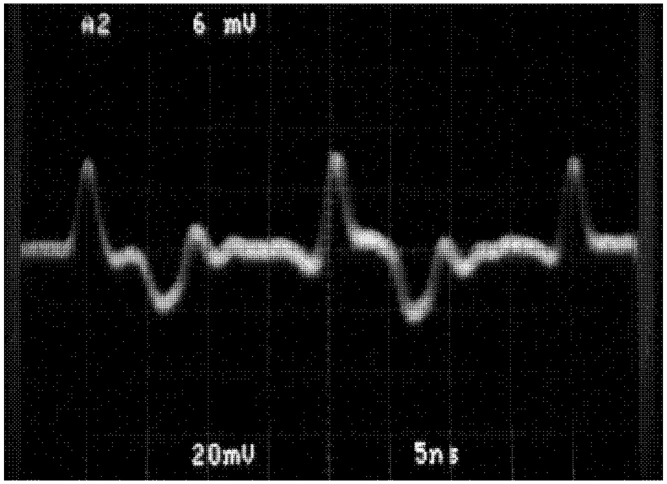


- Post-processing of Correlation Patterns
  - » High speed processing done in hardware
  - » Complex processing done in software
- Precise timing for Cooperative Ranging
  - » 10 ps resolution for scheduling of transmission & reception
  - » Sub-centimeter range resolution

Transmission

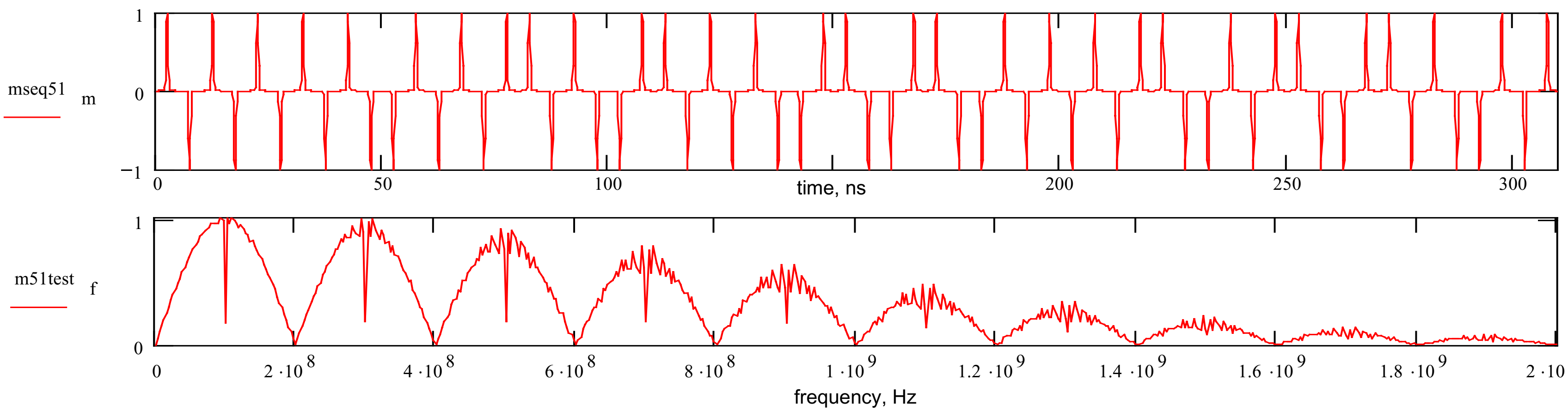
- Episodic transmission of Pseudonoise (PN) coded sequences of Impulse Doublets
  - » Impulse is launched when current is turned On or Off
    - – Radiation power is Derivative of current squared
  - » Bipolar signal (chip) allows use of CDMA codes including m-sequences, Gold codes, Kasami codes, etc.
  - » Impulse Doublets are optimally generated using CMOS switches



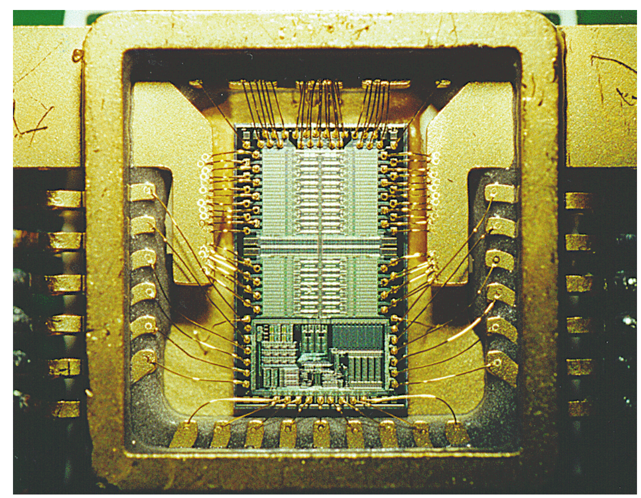


Transmission

- Spectral Nulls chosen by Impulse Separation to notch out frequency bands for transmission & reception (*i.e.* GPS)

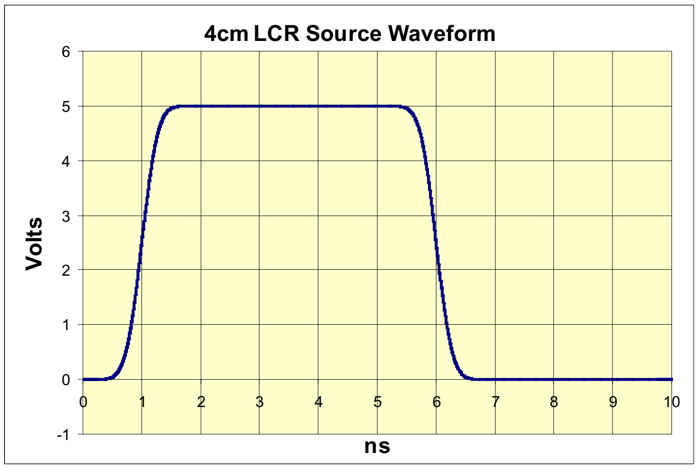


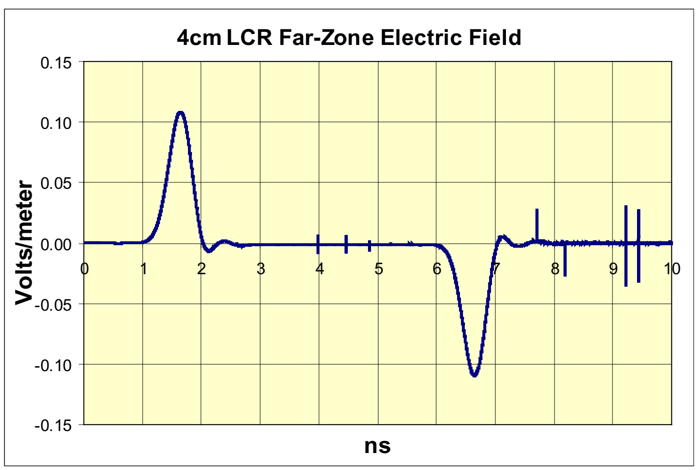
- Data Modulation (alone or in combination)
  - » Antipodal, Pattern-shift, M-ary codes
- Low-inductance custom chip package
  - » Multiple wire bonds for low inductance
  - » Large, low-impedance, direct-connect antenna leads

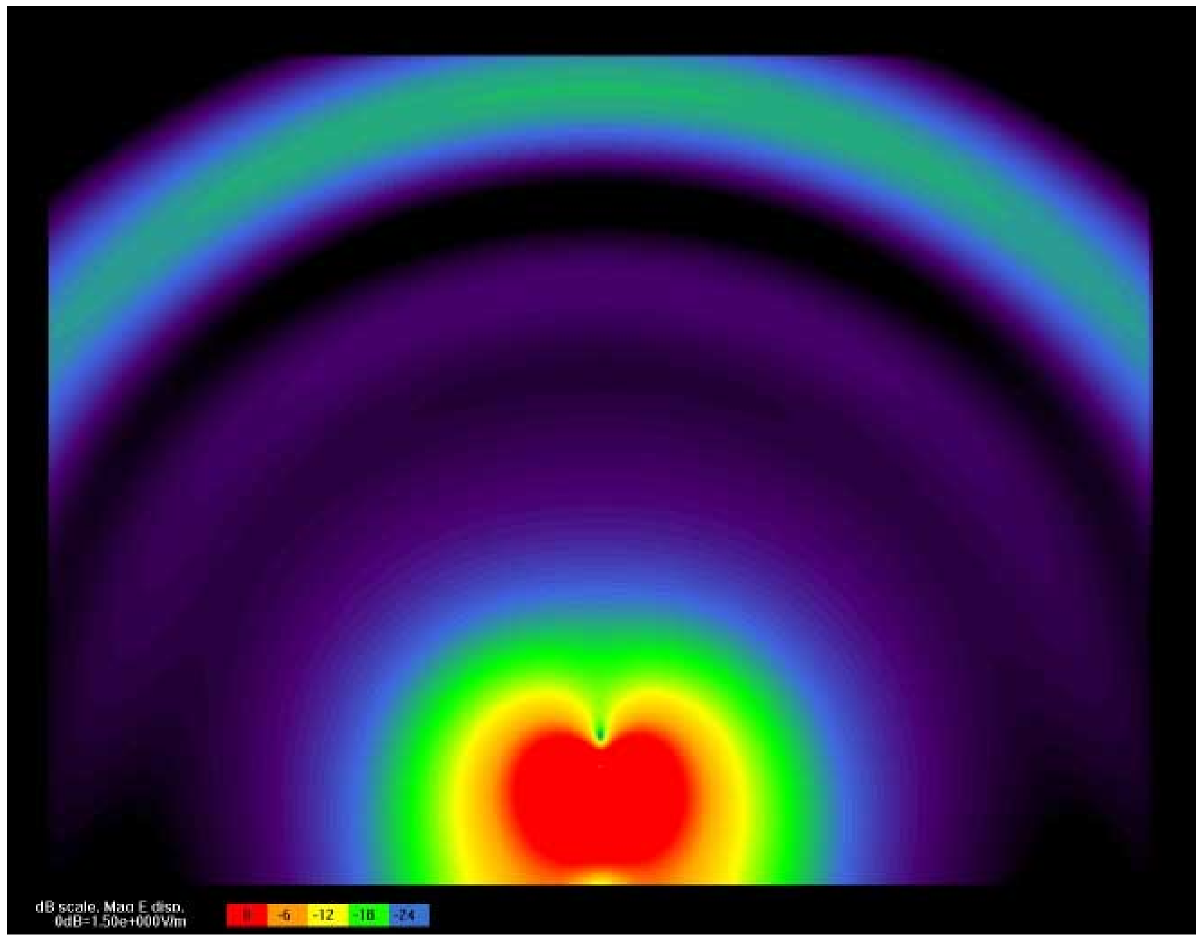


Large Current Radiator

Baseband impulses (<1GHz) can be effectively radiated from small (<4cm) Large Current Radiator (LCR) antenna *(FDTD simulation)*

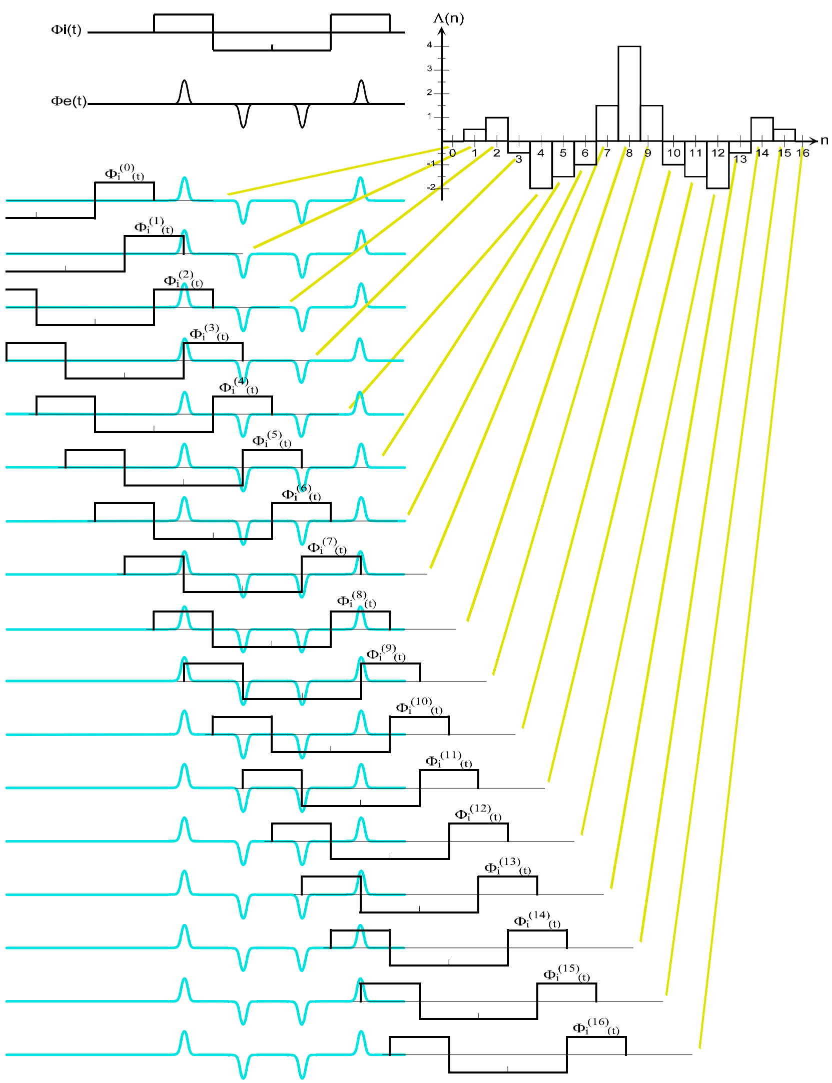






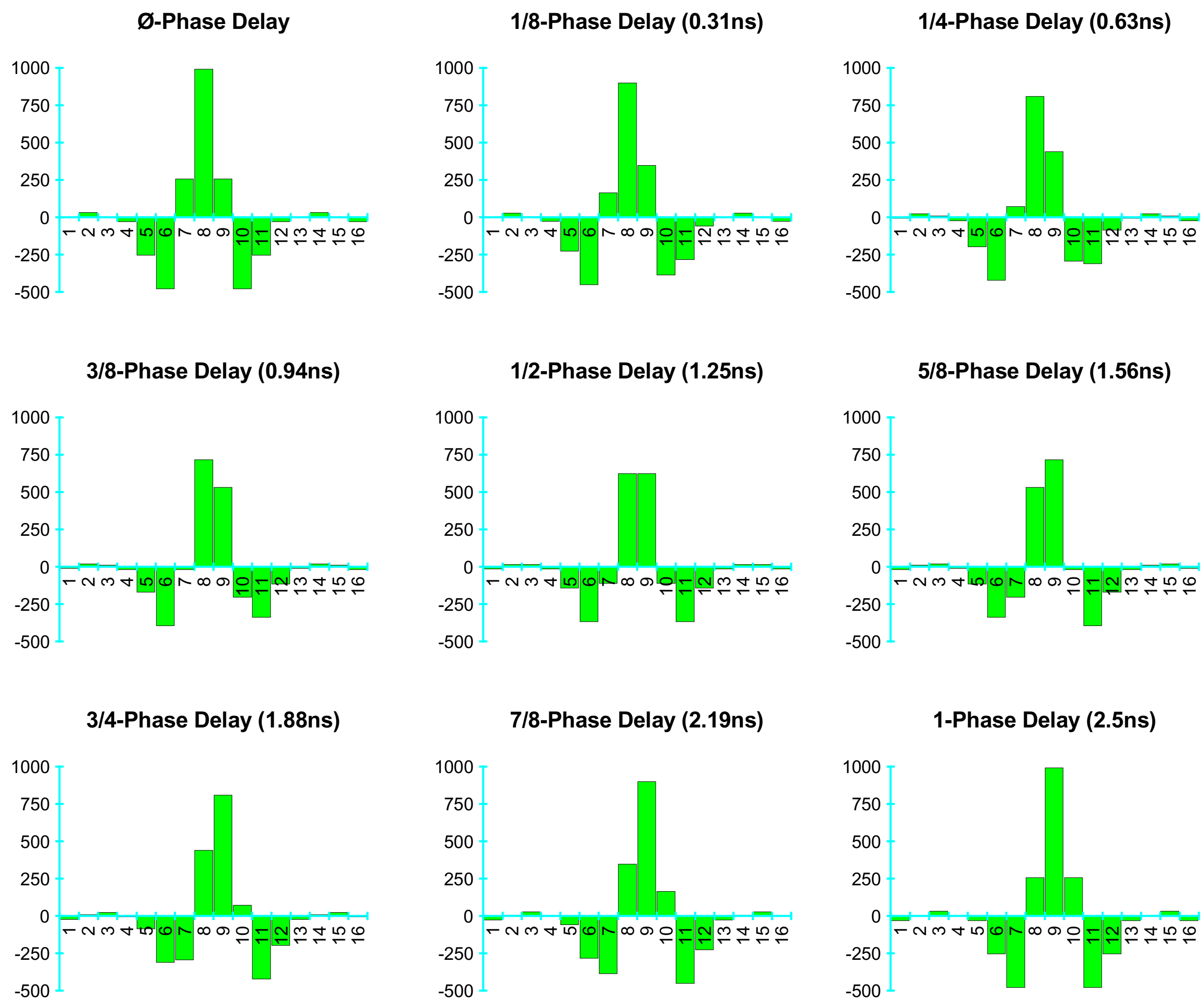
Reception

- Coherent Reception via Correlation
  » Time Integrating Correlator is a Matched Filter
    – Analog input signal is multiplied by Reference code & integrated
    – Each of 32 correlator phases represents a different time alignment of input signal & reference code
  » 30 dB Process Gain with families of orthogonal 1K codes
  » Typical <u>reception window is 80 ns</u> with 32 correlator phases spaced 2.5 ns apart



Time-Shift Patterns

- Output pattern of the Time-Integrating Correlator changes as the alignment of the received signal and reference code shifts
  - Each graph represents 1/8 phase shift or 312ps
  - A time shift of 2.5ns produces the same pattern shifted by one complete bin
  - "Odd" bins change more rapidly than "Even" bins when peak is centered on "Even" bin (and *vice versa*)



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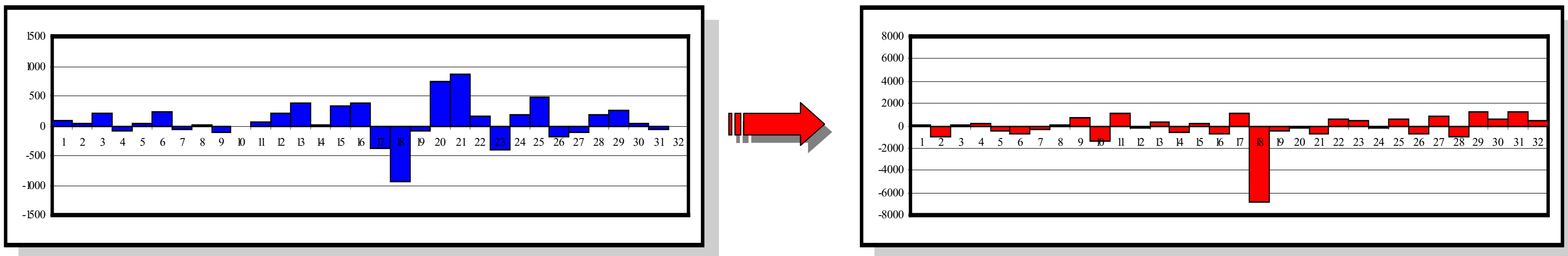
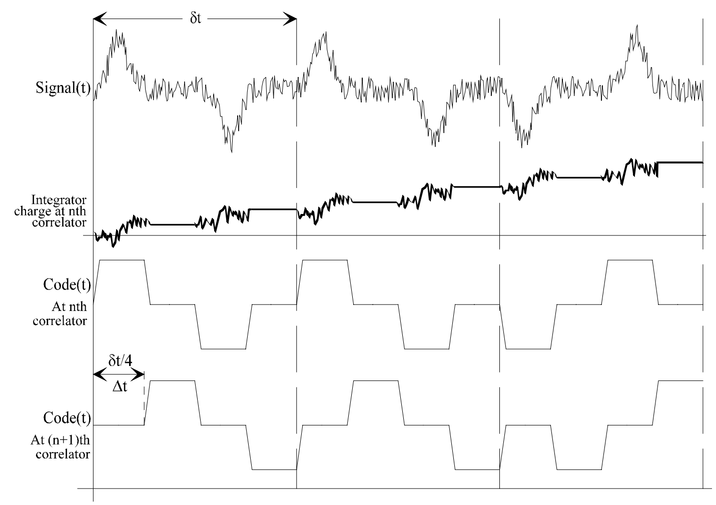
Detection & Time Domain Filtering

- Detection by pattern recognition of Correlator outputs
  - » Improved Bit Error Rate (BER)
  - » Multipath correction via channel equalization



- Time Domain Filtering to reduce noise
  - » Additional 7-10 dB increase in SNR
- RF Amplifier has flat group delay
  - » 1GHz bandwidth
  - » Passes impulses undistorted



Rapid Acquisition

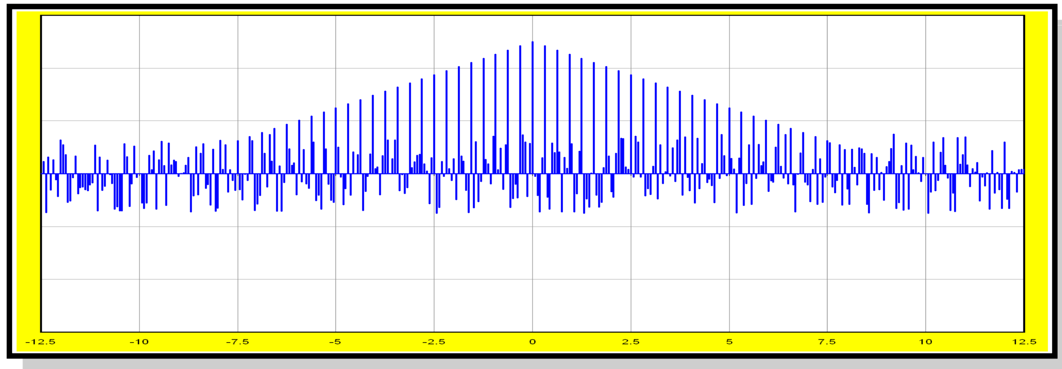
- Typical Time scales
  - » t_w = 80 ns – Correlator reception Window
  - » t_p = 10 μs – Beacon transmission Period = Listener reception Period
  - » t_c = 1 ms – Beacon signal Cycle time
- **Exhaustive Search**: Listener steps its reception window in increments of $t_c + (\alpha \cdot t_w)$; $\alpha < 1$ for overlap $t_c / (\alpha \cdot t_w)$ receptions
  - » Beacon detected when correlation peak is within reception window
- **Rapid Acquisition**: Listener steps its reception window in increments of $t_c + (\beta \cdot t_p)$; $\beta < 2$ $(t_c / (\beta \cdot t_p)) \cdot (t_m / (\alpha \cdot t_w))$ receptions
  - » Beacon detected when Beacon Tx and Listener Rx periods overlap
  - » Beacon Code autocorrelation pattern has pyramidal shape
- **Speedup Factor**
  - » Exhaustive / Rapid = $(\beta \cdot t_p) / t_m = \beta \cdot (2^n - 1)/(2^{n/2} - 1) = \beta \cdot (2^{n/2} + 1)$
    - – For 1023-chip codes, n = 10, and β = 1, speedup factor is **33**

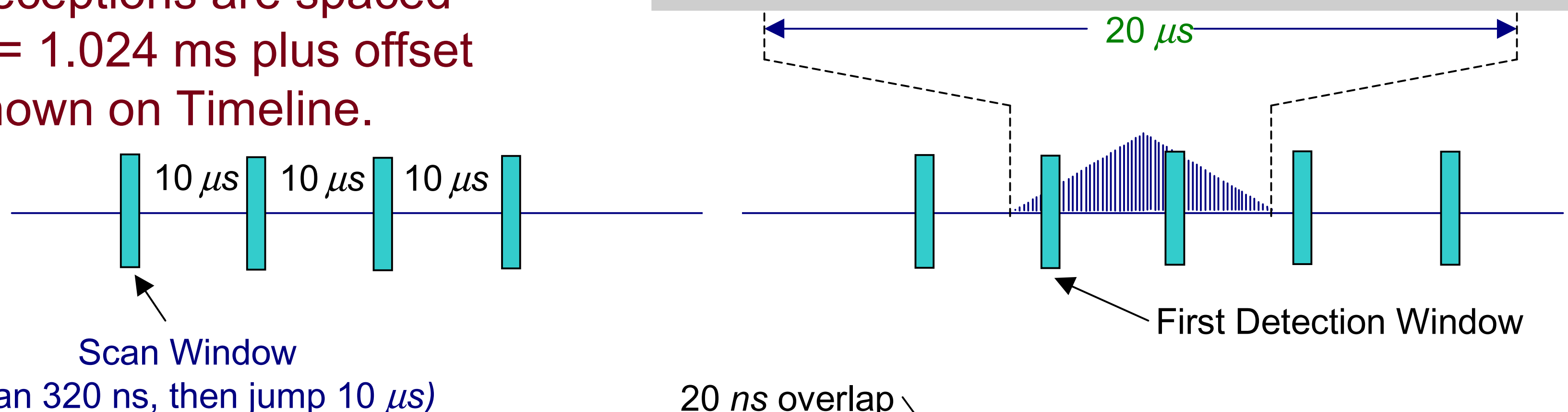
Rapid Acquisition

Received correlator output of **Beacon** signal plus noise.

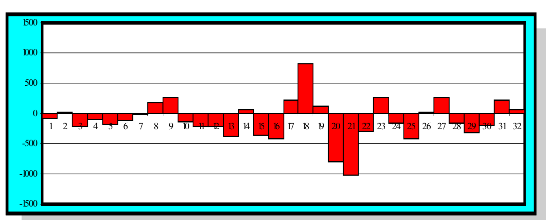
Peaks exist every t_m = 310 nanoseconds.

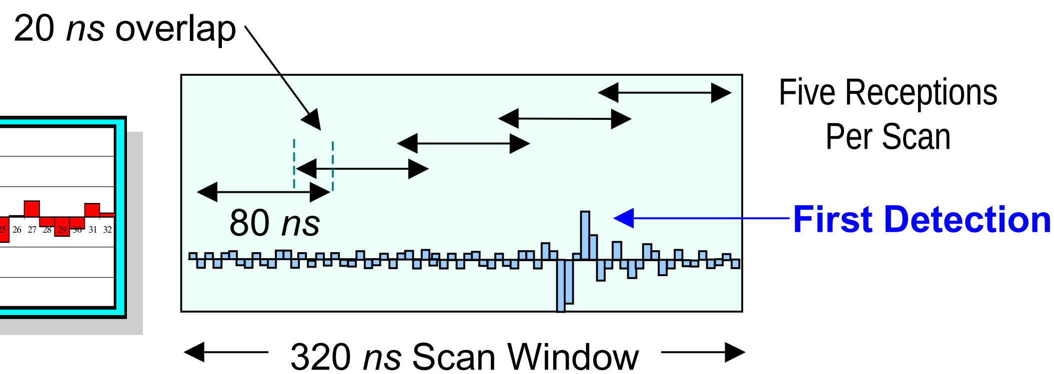
Receptions are spaced t_c = 1.024 ms plus offset shown on Timeline.





Correlator window Size t_w = 80 ns





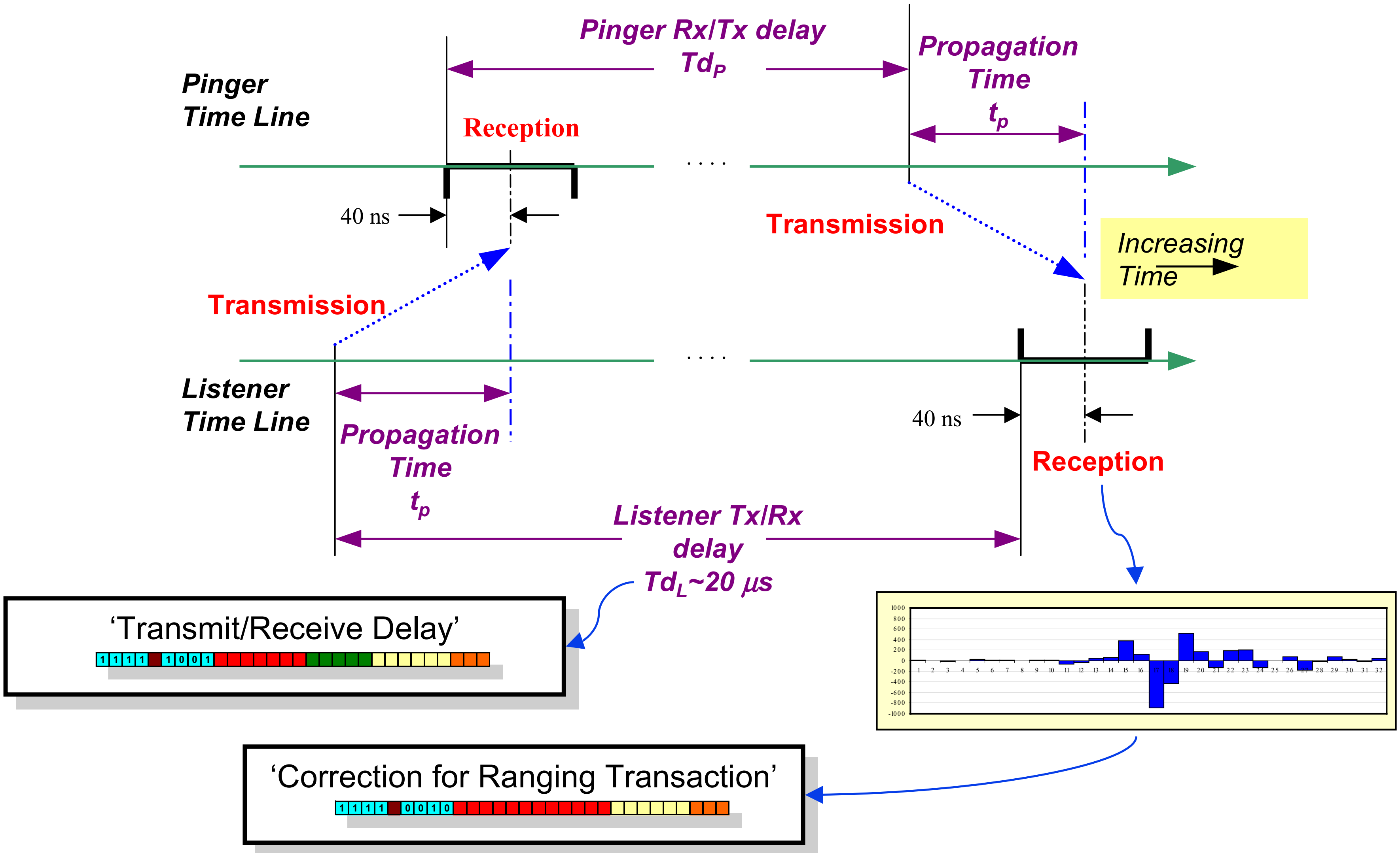
Cooperative Networking

- Position location using inexpensive timebases
  - » Quartz crystal or MEMS oscillator
    - – 1 ppm (10^{-6}) with on-chip software-mediated temperature compensation
    - – Localizers track each other's clock frequencies for ppb (10^{-9}) matching (*i.e.* Consensus Clock)
  - » Absolute position accuracy of entire network is raised to the absolute accuracy of the best oscillator or known distance
- Code & Time Division channelization for a million Localizers per km^2
- Multi-hop communication
  - » Defeats $1/R^n$ received power reduction ($n \geq 3$)
  - » Reduces probability of intercept
- Selective sharing of data over network
- Capable of hiding ranging information (for Security)
  - » Synchronization without giving range
  - » Spoofing for privacy

Signal Structure

- Short Duration Episodic Transmissions
  - » Very low power operation achievable with low duty-cycle
    - – Typical 1% duty cycle with 1 ms cycle time
    - – Network precise timing (~1ppb) allows extended sleep mode (~40s)
  - » Coherence maintained over typical 10 μs reception window
    - – Time compression spread < 10 ps with 1ppm timebase
    - – Doppler shift insignificant for less than orbital velocity
    - – Each reception starts with zero integrated noise
  - » Back-and-forth Ranging exchange spans ~20 μs
    - – Better than 1 cm absolute accuracy with 1ppm timebase
    - – Digital post-correction of actual versus expected arrival time
- CDMA operation requires both low autocorrelation sidelobes and low cross-correlation within a family of PN code sequences
  - » Maximal sequences have ideal auto-correlation, but small families
  - » Small & Large Kasami and Kasami-like codes have useful families

Ranging Transaction



OSI Model - Data Link Layer

- Media Access Control
  - » Code-Division Multiple Access (CDMA) minimizes collisions between non-communicating units and between non- or weakly-linked clusters
    - – 32 Small Kasami codes (or 32,800 Large Kasami codes)
  - » Time-Division Multiple Access (TDMA) within local cluster
    - – 32 slots per Epoch, each 31.25 μs long
  - » Duplex exchange of 1 Burst (1 or more bits) within 31 μs slot
    - – Allows short "moment arm" for round-trip ranging exchanges
- Logical Link Control
  - » 29-Bit Packet: preamble(1), header(5), payload(16), ECC(6), ranging(1)
    - – Scheduled modulo reservation look-ahead cycle time (~32 packets)
    - – Packet boundaries are negotiated between pairs of Localizers
    - – TDMA allows packet exchanges between pairs of Localizers to overlap
    - – Time-stamping for aging location fixes and tracking movement

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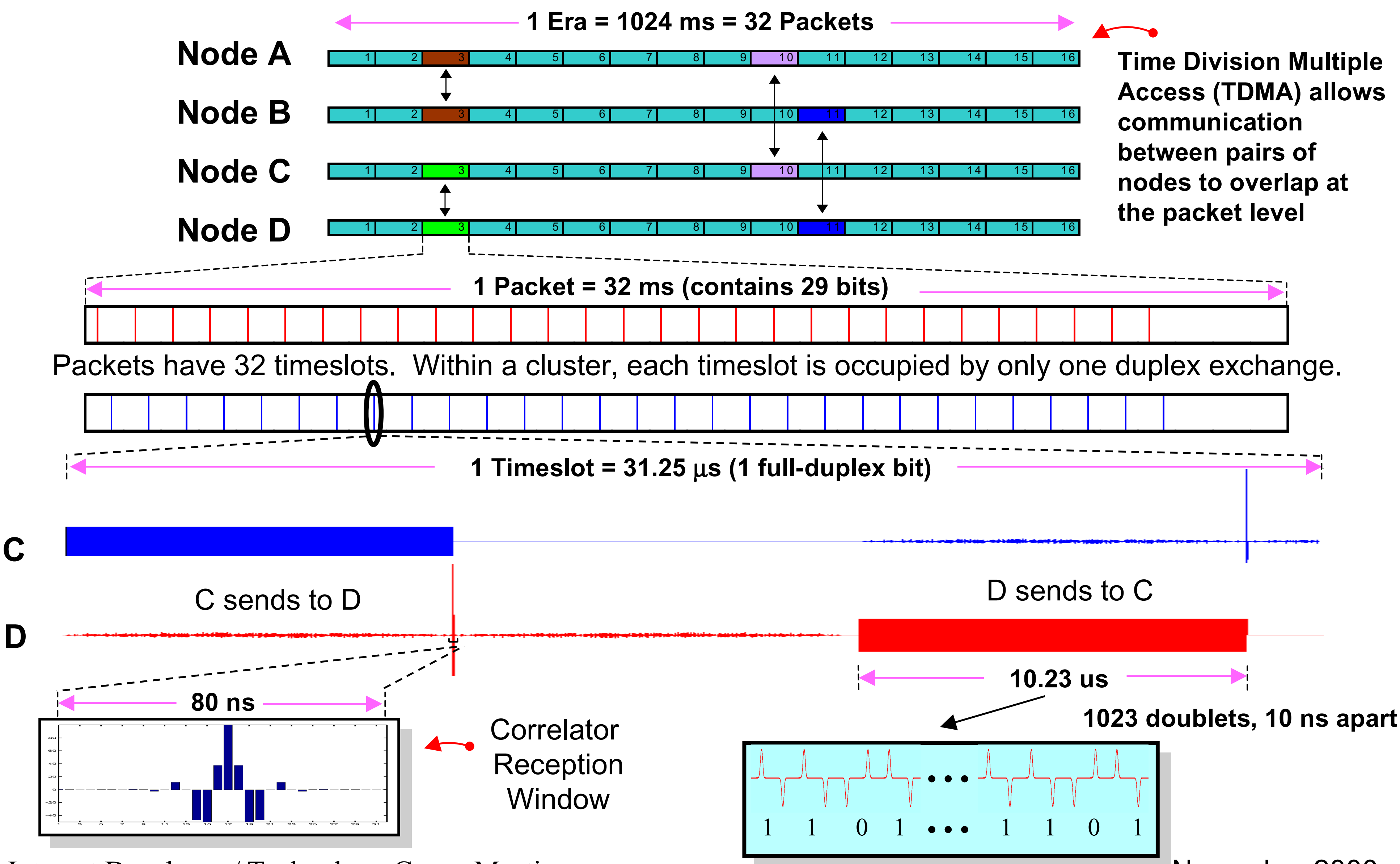
TDMA

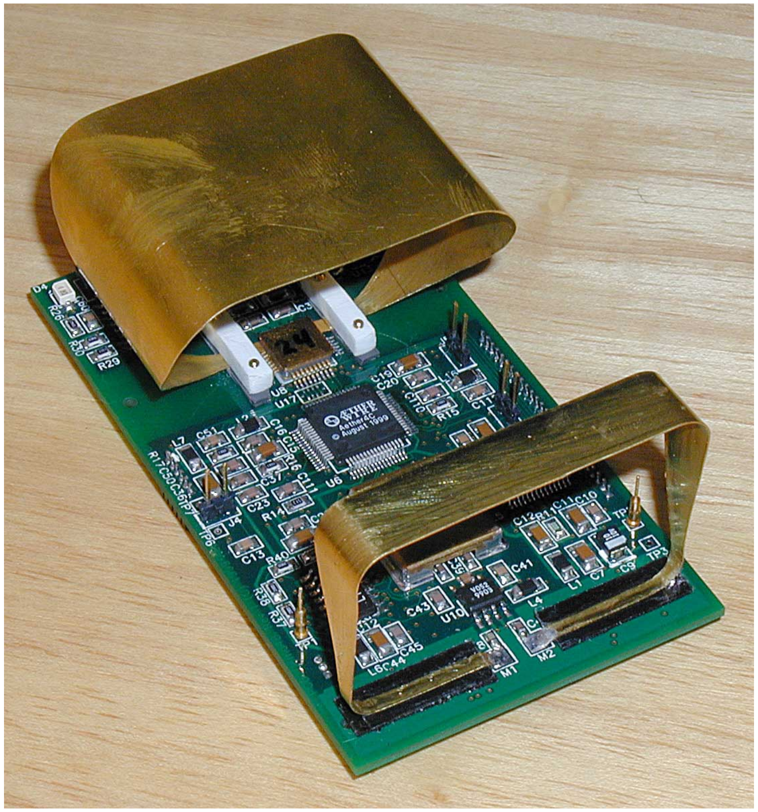


Saving Power

- Low-duty cycle Episodic transmission/reception
  - » Scheduled wake-up
  - » 80μs RTOS tick
- Ad-hoc networking using multi-hop
  - » Special rapid acquisition codes / algorithm
  - » Matchmaking further deduces acquisition time
- Current mode low voltage differential swing (LVDS) logic
  - » Lower power than standard CMOS at high clock rate
  - » 24 DAC's to adjust current to match speed requirements
- Multi-stage time-of-day clock
  - » Synchronous counter / current mode logic for highest speed stages
  - » Ripple counter / static CMOS for lowest speed stages
- 9 separate sections that can be powered-down
- Compute-intensive correlation done in analog hardware

Hardware Prototype

- Pager-sized 4th Generation Prototype
  - » Transmit/Receive
    - – Rx/Controller chip (Aether5)
      - Closed loop sensor
      - Low-noise TCXO
    - – Tx Antenna Driver chip (Driver2)
      - Large Current Radiator
    - – External RF amplifier & DAC
    - – A-to-D converter
  - » Processor
    - – Motorola ColdFire 5204
    - – 1MB Static RAM
    - – 512KB Flash RAM
  - » Power regulation



Hardware Prototype

- Low-Noise Logic family (to minimize Reception noise floor on-chip)
  - » < 1 µA switching noise per gate on power supply
- Receiver/Controller chip (Aether5)
  - » 32-phase Time Integrating Correlator
  - » 60 dB variable gain RF amplifier (to adapt to large range of input signals)
  - » Real Time Clock (Tx/Rx event register & comparators)
    - – 200 MHz low-jitter Phase-Locked Loop
  - » Tx/Rx code sequence generator (25-stage LFSR)
    - – 1023 length Large Kasami codes (32,800-member families)
  - » 26 Independent Power Controls (for very low power operation)
- Transmit antenna driver chip (Driver2)
  - » H-bridge for producing Bipolar radiated impulses (+ or -)
    - – Can Drive 8 amps with 450 ps edges (0.2 Ω output impedance)
  - » Eight independent edge-delay controls

Contact Information

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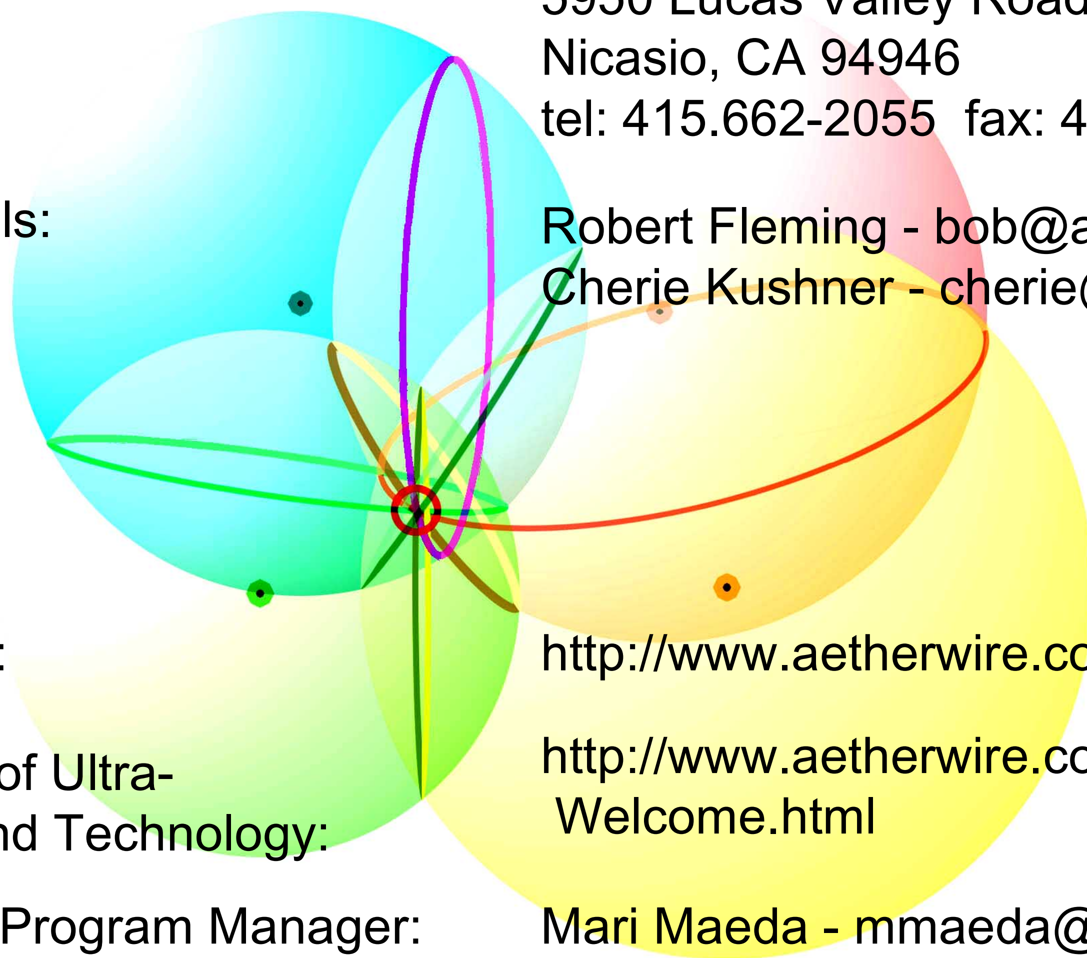

- Website: http://www.aetherwire.com/

- Archive of Ultra-Wideband Technology: http://www.aetherwire.com/CDROM/Welcome.html

- DARPA Program Manager: Mari Maeda - mmaeda@darpa.mil

DARPA

A Killer Application

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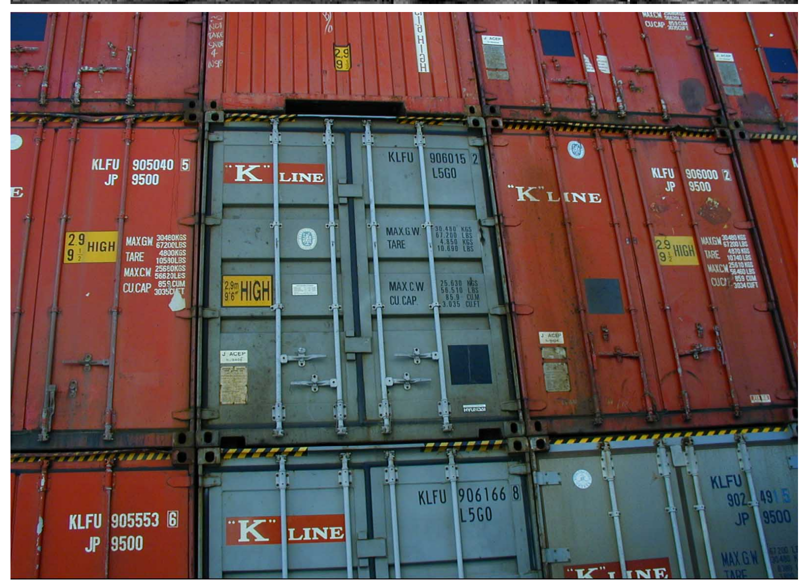
- The Problem: Desert Storm
  - » First Major Regional Contingency (MRC) with ISO Containers
    - – 40,000 Containers, Opened 25,000
      - Paper Manifests Were Inaccurate and Easily Lost
    - – ISO Containers <u>Hid the Stuff</u>
      - Previous MRCs Used Break Bulk
    - – Misplaced & Lost Stuff = $3 Billion
      - GAO Report B-246015, Dec 1991
- Autonomous Manifesting
  - » The “Holy Grail of Logistics”
    - – Multipath reverberation $\Rightarrow$ 1 μs
    - – Internal / stacked container blockage
    - – RF leakage thru floor and doors
    - – 1-3 inch resolution for inside *vs.* out



Autonomous Cargo Manifesting

Antennas: Farr Research TEM horns

Transmitter: Picosecond Pulse Labs model 2600 pulse generator

Receiver: Tektronix TDS694C 10 GS/s, 3 GHz digital storage oscilloscope

- Autonomous Manifesting of ISO Cargo Containers using Localizers
  - » DARPA-sponsored research applied to Navy problem
  - » Testing supported by ONR (Steve Gunderson, steve@nfesc.navy.mil)
    - – Initial Tests
      - Port of Oakland, 25 May 2000
      - Characterize the RF environment
      - Measure multipath delay spread
      - Measure leakage and noise
    - – Demonstration
      - Port of Oakland, Spring 2001
      - Hide & Seek Localization Tests: which container has the asset
      - Measure Localization accuracy

RF in ISO Containers

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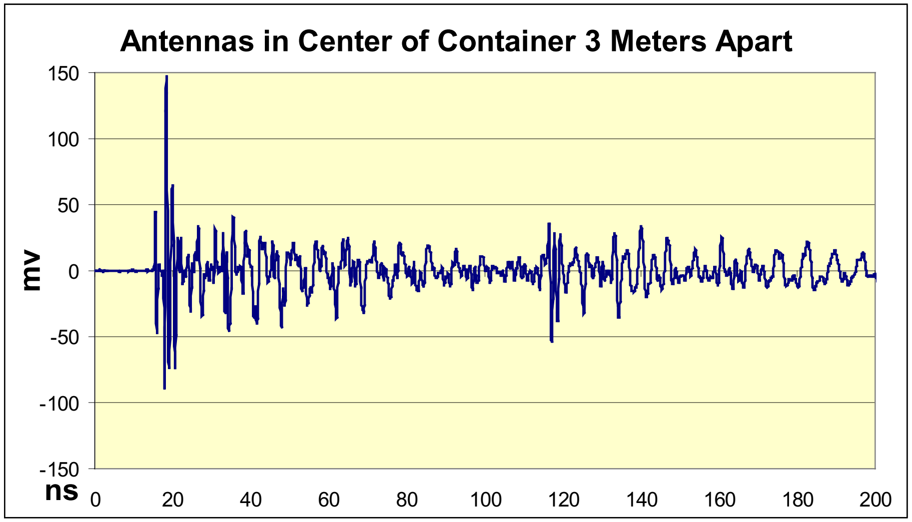
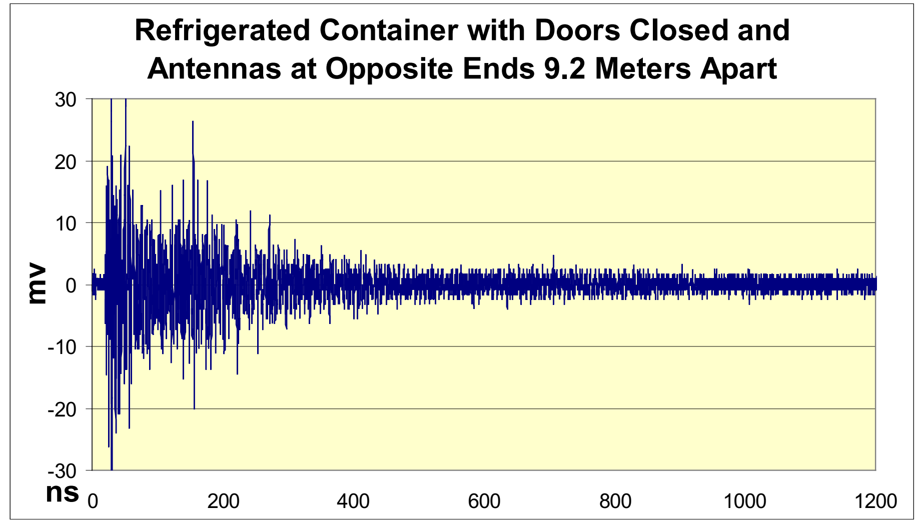
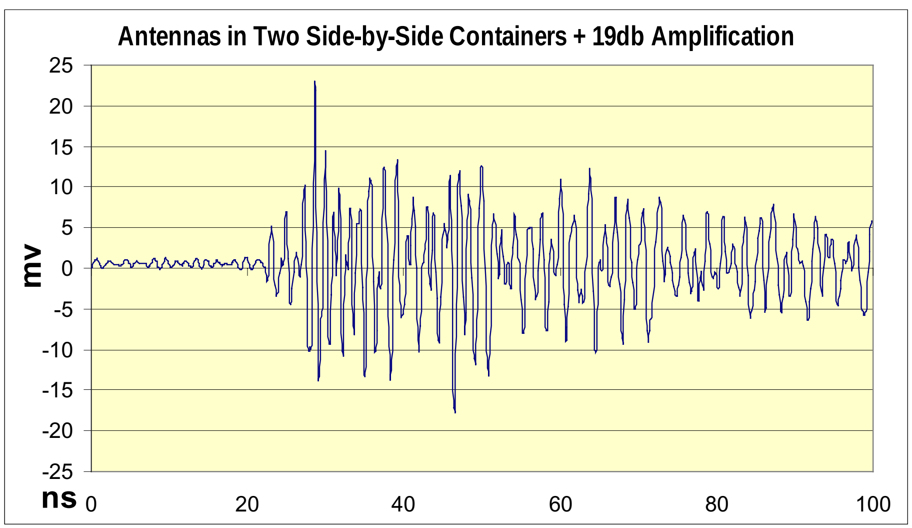
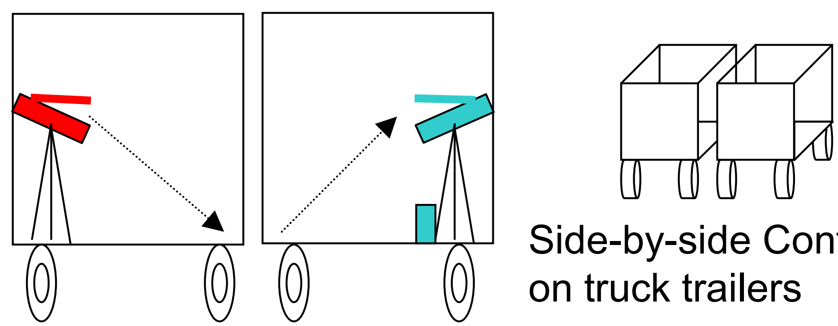


Direct path signal dominates multipath at 3 meters



Worst case delay spread 1 μs in Refrigerated Container with metal walls on all six sides



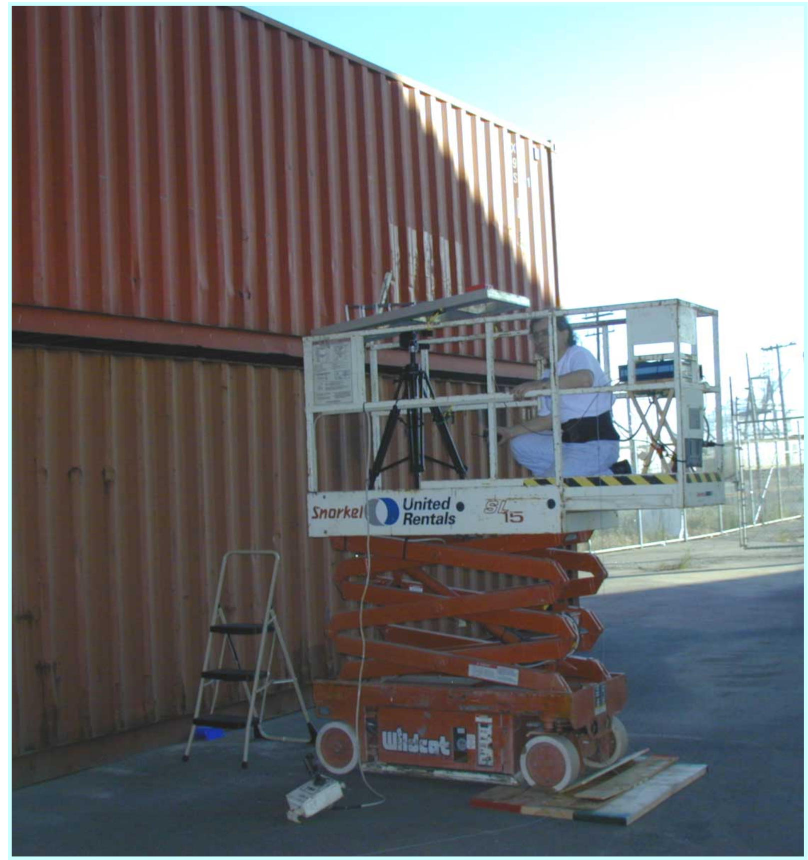


Side-by-side Containers on truck trailers

The leakage between containers thru the wooden floor is significant when they are not on the ground

Autonomous Cargo Manifesting

- The Challenge: ISO Containers
  - » Multipath delay spread ⇒ 1 μs
    - – Direct path dominates multipath at short range (~3 meters)
    - – More correlators / smaller windows
    - – RAKE signal processing of multipath
  - » Absorption and blockage
    - – Nearest neighbor communication
    - – Projection of position determination using network linkages (*i.e.* a truss)
- ACM System Development
  - » System-on-chip to minimize cost
  - » Polarization diversity for orientation
  - » Battery life ⇒ months
    - – Extremely low duty-cycle
    - – Alternative wake-up modality



Measuring leakage thru wooden bottom and out between stacked containers